TITLE: A New Type of Surface Waves on the Open Metallized Nanowires

7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

A new type of surface waves on the open metallized nanowires

N. S. Averkiev, *S. O. Kognovitsky*, R. P. Seisyan and V. V. Travnikov
Ioffe Physico-Technical Institute, St Petersburg, Russia

Abstract. The present work is devoted to the investigation of light interaction with a grating array of metallized nanowires on a semiconductor surface. Specular reflection spectra of such structures for two orthogonal incident light polarizations have been studied as a function of geometrical parameters of structures. Very strong polarization contrast in some spectral intervals has been found. A specific type of "grating surface" waves has been proposed to explain the obtained results. The calculation of reflectivity spectra for TE and TM polarizations has been performed using the effective anisotropy layer model.

Introduction

Specific optical properties of periodical arrays of open metallized semiconductor nanowires are due to both the grating effect and peculiarities of light interaction with metals (for example the scattering on surface plasmon polaritons (SPP)). In particular, the specific "grating" electromagnetic waves may be excited. As follows from [1], one of such modes may be a hybrid combination of the sliding diffraction mode with waveguide modes localized at the grooves. SPPs on the surface of the deep sinusoidal metal grating may form standing waves with an essentially unhomogeneous distribution of the energy density across the grating groove direction [2]. In this work, it is shown that a specific "grating surface" electromagnetic wave (GSEMW) may propagate along the surface of the short-period lamellar grating and perpendicular to the wire direction. This wave is a coupling state of standing waves localized at deep grating grooves and surface electromagnetic waves of a plasmon type on the metal-air interface of wire tops.

1 Experiment

To investigate optical properties of wire arrays, the set of open metallized lamellar gratings was fabricated. Initial gratings were manufactured from a semi-insulating GaAs by the method of the reactive ion etching through the strip mask made with using the optical interference lithography. Then these semiconductor gratings were covered by an Au layer with the help of the thermal vacuum evaporation. Two values of the Au layer thicknesses were used. On the tops of wires and on the bottoms of intervals between wires, the Au layer thickness (d) was either $d \approx 60$ nm or $d \approx 25$ nm. The corresponding thickness (g) of Au on side (vertical) walls of wires was either $g \approx 25$ nm or $g \leq 15$ nm. The obtained gratings consisted of wires of almost rectangular cross-sections. The wire width was equal to about half of the grating period. The structures from the grating set are varied in period ($p = 250, 310, 370, 420$ nm), in depth ($h = 80, 200, 280$ nm) and in thickness of Au.

Spectra of the specular reflection from grating samples were measured in the wide range of wavelengths (400–1500 nm) at room temperature. Experiments were carried out at the strict normal incidence to sample surfaces of the collimated (0.5°) beam of the white light. The polarization of both incident and reflected beams was chosen either parallel (TE) or perpendicular (TM) to the wire direction. The obtained results are presented as spectral dependencies of the ratio between the reflectivity of TE polarized light (R_{TE}) and the reflectivity of TM polarized light (R_{TM}).

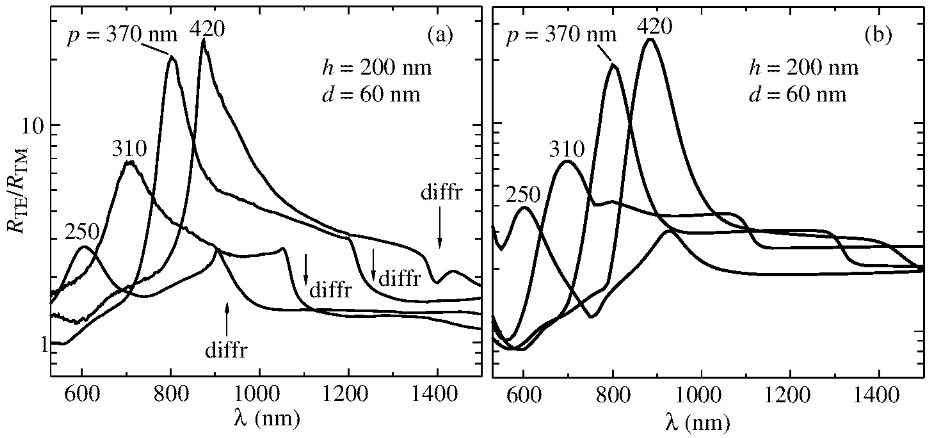

Fig. 1. The measured (a) and calculated (b) spectral dependence of the ratio between the reflectivities of TE and TM polarized light for structures with different grating periods.

The series of the strong maxima have been found in the polarization contrast spectra. The values of some maxima achieve 100 for the case of the deep grating (h = 200, 280 nm). For shallow gratings (h = 80 nm), these maxima are much smaller. Their spectral position does not depend practically on the wire height and thickness of the Au layer, but it strongly depends on the grating period (Fig. 1(a)). These maxima appear due to existence of corresponding minima in the reflection spectra for the perpendicular polarization (TM).

2 "Grating surface" electromagnetic waves

We have associated the origin of minima in TM reflection spectra with a leakage of a part of the intensity of the perpendicular polarized (TM) incident beam to the specific waves of a surface type named below as the "grating surface" electromagnetic waves (GSEMW). These waves propagate along the grating surface and perpendicular to the wire direction. GSEMWs are coupling states of surface electromagnetic waves of a plasmon type on the metal-air interface of wire tops and waveguide-type waves localized at deep grating grooves. The waves inside grooves are standing along the normal to the grating surface and polarized perpendicular to the wire direction. Propagation of GSEMW crosswise the wire direction is synchronized by the grating period so that longitudinal components of the wave electric field E inside adjacent air intervals between wires are oppositely oriented. Because of this, the surface wave period must be equal to two grating periods. This fact is in a good agreement with theoretical predictions that the waves of a surface type appear to exist on arrays of metallic wires in the range of incident light wavelength greater then two grating periods [3]. At normal light incidence, a standing superposition of GSEMWs is excited.

The short-period deep grating structure may display itself as an effective homogeneous anisotropic uniaxial medium with average optical parameters. The method of evaluation of effective refractive indexes of such medium was described in [4] and was used at studies of bulk wave reflection from surface gratings.

We have proposed to use the approach of effective medium for analysis of surface type waves. The well known dispersion dependence of a surface electromagnetic wave [5] may be applied to the surface wave which is localized on the interface between the effective

medium of grating and air. By this means, the wavelength of GSEMW may be estimated as:

$$\lambda_{\text{surf}} = 2\pi / Re\left(2\pi\sqrt{\varepsilon_{\text{eff}}/(\varepsilon_{\text{eff}}+1)}/\lambda\right), \tag{1}$$

where λ is the wavelength of the incident light in vacuum, ε_{eff} is the effective complex dielectric constant of grating top. For waves propagating across the wire direction, the ε_{eff} may be consisted with using "geometry averaging":

$$\varepsilon_{\text{eff}} = ((p-b)\varepsilon_{\text{air}} + b\varepsilon_{\text{Au}})/p, \tag{2}$$

where p is the grating period, b is the wire width, ε_{Au} is the complex dielectric constant of Au [6], ε_{air} is the air dielectric constant chosen equal to 1.

In according with the proposal model of GSEMW, the wavelength of this wave is equal to two grating periods: $\lambda_{\text{surf}} = 2p$. In this manner, the values of wavelengths of the incident light corresponding to the resonant excitation of GSEMWs may be found for all fabricated gratings from Eq. (2). These values coincide well with the spectral positions of main maxima in the experimental polarization contrast spectra ($R_{\text{TE}}/R_{\text{TM}}$). This points to the fact that these maxima are largely due to efficient interaction of GSEMWs with the incident light polarized perpendicular to the wire direction at the corresponding frequencies. This interaction plays a significant role in formation of polarization anisotropy of reflecting properties of metallized short-period deep gratings.

3 Analysis of the polarization anisotropy of reflectivity spectra

Besides excitation of GSEMWs, the polarization anisotropy of reflection is determined by other mechanisms like interference and diffraction. It is important to separate the contribution of GSEMW excitation. For this purpose, specular reflectivity spectra were calculated for cases of TE and TM polarized insident light (R_{TE} and R_{TM}) in the framework of the effective layers model [11].

Effective medium of the gratings is considered as consisting of three effective homogeneous anisotropic layers lying on the GaAs substrate. These layers are short-period gratings composed of: (1) Au tops of wires separated by air intervals, (2) GaAs wires with gilded walls also separated by air intervals, (3) Au wires lying on air interval bottoms and separated by GaAs. Each layer ($s = 1, 2, 3$) is described by two effective complex dielectric constants $\varepsilon_s^{\text{TE}}$ and $\varepsilon_s^{\text{TM}}$ for the light polarized parallel and perpendicular to the wire direction respectively:

$$\varepsilon_s^{\text{TE}} = [(p-b)\varepsilon_s^{\text{spl}} + (b-2g)\varepsilon_s^{\text{wire}} + 2g\varepsilon_{\text{Au}}]/p, \tag{3}$$

$$\varepsilon_s^{\text{TM}} = p/\left((p-b)/\varepsilon_s^{\text{spl}} + (b-2g)/\varepsilon_s^{\text{wire}} + 2g/\varepsilon_{\text{Au}}\right), \tag{4}$$

where $\varepsilon_1^{\text{wire}} = \varepsilon_{\text{Au}}$, $\varepsilon_{2,3}^{\text{wire}} = \varepsilon_{\text{GaAs}}$, $\varepsilon_{1,2}^{\text{spl}} = \varepsilon_{\text{air}}$, $\varepsilon_3^{\text{spl}} = \varepsilon_{\text{Au}}$.

The difference between $\varepsilon_s^{\text{TE}}$ and $\varepsilon_s^{\text{TM}}$ determines the polarization anisotropy of reflectivity of grating in a wide spectral range.

Reflectivity for each light polarization (R_{TE} and R_{TM}) has been calculated taking into account the reflections from four surfaces of effective anisotropic layers. Light interference between these surfaces influences strongly on reflectivity in the particular spectral range. This influence is found significantly different for TE and TM cases.

The contribution of the interaction of the light with GSEMWs into the formation of the polarization anisotropy may be described by the decrease of both the transmittance and the

reflectivity of the top boundary of the upper layer ($s = 1$) for the TM polarized light in the vicinity of GSEMW resonance excitation.

The diffraction has a large influence on the reflectivity spectra shape. The diffraction into the air is absent at the experimental geometry under study. But the diffraction into the substrate takes place in certain spectral ranges. This leads to a leakage of a part of incident light intensity to diffraction orders. In calculations of spectra this fact may be taken into account by the decrease of reflectivity from the bottom of the lowest effective layer ($s = 3$) of the structure when forming diffracting beams in the vicinity of this layer.

In this way the spectral dependence of the reflectivity ratio R_{TE}/R_{TM} has been calculated using real geometrical structure parameters and optical properties of structure materials. The set of the polarization contrast spectra obtained by this manner is shown in Fig. 1(b).

The comparison between experimental data and the calculations allows to clear the origin of several spectral features. The occurrence of long-wavelength spectral peculiarities in the range of the GaAs transparency (marked on the experimental spectra as "diffr") is determined by the light diffraction to the substrate. Short-wavelength minima in the polarization contrast spectra are largely due to the light interference.

4 Conclusion

A new type of the "grating surface" electromagnetic waves with wavelengths exceeding the grating period has been identified. We have suggested a new method of description of electromagnetic waves on the surface of short-period deep gratings using an effective medium model. This method is characterized by a simplicity and a versatility. A good agreement between experimental and calculated data has shown the significant role of the excitation of GSEMWs in the formation of reflection spectra from the structures with open metallized nanowires. The influence of interference and diffraction light on polarization anisotropy of reflectivity has determined.

The authors wish to thank Prof. V. A. Kosobukin for useful discussion and Dr. L. G. Rotkina for the important contribution to fabrication of investigated samples. One of the authors (R.P.S.) wishes to thank Professor A. A. Maradudin for interesting discussion.

References

[1] T. Lopez-Rios et al., *Phys. Rev. Lett.* **81**, 665 (1998).
[2] R. A. Watts, T. W. Preist and J. R. Sambles, *Phys. Rev. Lett.* **79**, 3978 (1997).
[3] V. P. Shestopalov et al., Diffraction of waves on grating, *Izd. Khar'kovskogo Universiteta*, Khar'kov, 1973, (in Russian).
[4] P. Yeh, *Optics Communications* **26 (3)**, 289 (1978).
[5] V. M. Agranovich, *Uspekhi Fizicheskikh Nauk* **115**, 199 (1975), (in Russian).
[6] P. B. Johnson and R. W. Christy, *Phys. Rev. B* **6**, 4370 (1972).